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Improved Sand Transport Model for LTFATE (Version 2.0)

PURPOSE: Long-Term FATE of dredged material (LTFATE) model is a combined local hydrodynamic and sediment transport model used to determine the long- and short-term stability of dredged material mounds. This Technical Note (TN) describes a more accurate, replacement, sand transport submodel that has been incorporated into LTFATE.

BACKGROUND: The LTFATE model includes two sediment transport methods, cohesive and noncohesive. The user specifies which type of transport is being simulated in the input file. This decision is based on an understanding of the dredged material mound composition being analyzed. Predominately sandy mounds where interparticle forces between grains are small compared to gravitational forces are modeled as noncohesive. Sediments that contain sufficient fines are modeled as cohesive. A description of the LTFATE cohesive sediment transport routines is provided in Gailani (1998).

The amount of fine-grain material needed to make sediment behave in a cohesive manner is a function of several variables, including mineralogy, organic content, and grain-size distribution. There is no formula available for making this decision. However, for screening level efforts, it can be assumed that sediment containing less than approximately five to eight percent (by weight) smaller than 10 μm and a majority of the material greater than 80 μm (sand-size) can be considered noncohesive. This does not hold true in all cases. For some very cohesive fine sediments, such as bentonite, fractions less than two percent can make a predominately sand (100 μm) sediment behave as a cohesive material (Gailani et al. 2001). Erosion experiments are the best method for determining if the sediment of interest is cohesive. However, general knowledge of the sediment, visual analysis, or rules of thumb can be used when erosion data are not available. LTFATE Version 2.0 requires that the user has determined a priori if the sediments are cohesive or noncohesive .

LTFATE Version 1.0 (Scheffner et al. 1995; Scheffner 1996) simulated sand transport using a total load formula developed by Ackers and White (1973). The model simulates this total load movement as bed load. The version of LTFATE described in this TN includes methods for estimating both suspended and bed load of sandy sediments. The method developed by van Rijn (van Rijn1989a,b; 1993) has been incorporated into the LTFATE model. Compared to the Ackers and White method, the van Rijn method has been more rigorously tested and compared to data in high-energy and wave-dominated regimes. Therefore, Version 2.0 permits more accurate simulation of sand transport, particularly during high-energy events, where some sand is in suspension and can be carried long distances before redeposition.

Van Rijn Sand Transport Algorithms. The van Rijn sand transport routines incorporated into LTFATE Version 2.0 were designed and calibrated for nonbreaking wave conditions. Therefore, they do not include suspension and transport induced by breaking waves and are not appropriate for the surf zone. The routines do estimate wave asymmetry and are therefore designed for nearshore,

nonbreaking wave conditions. The method developed by van Rijn (1993; 1989a,b) is time-averaged over a wave cycle for suspended load and time varying for bed load. Wikramanayake and Madsen (1994) and others criticize time averaging as missing the spikes in concentration caused by passage of the trough and peak of the wave. However, LTFATE grids have minimum cell size on the order of tens of meters and time-steps of a wave period or larger. Breakdown into smaller grid cells or time-steps that would be required to monitor concentration variation over a wave cycle is not practical. In addition, the adopted method has been shown to reasonably simulate suspended transport and time-averaged suspended concentrations (van Rijn 1993).

The method, as coded in the van Rijn TRANSPOR routine for transport at a point (van Rijn 1993), requires as input water depth, depth-averaged current velocity, grain-size distribution, angle between wave and current direction, current and wave related bed roughness, fluid temperature, and salinity. The model will calculate wave asymmetry based on wave and water depth conditions. Wave asymmetry is assumed to affect bed load, but not suspended load horizontal fluxes.

Dimensionless Parameters. Three dimensionless parameters are used in the van Rijn method. The dimensionless particle parameter D_* reflects the influence of gravity, density, and viscosity on sediment particles.

$$D_* = d_{50}\left[(s-1)g/v^2\right]^{1/3} \tag{1}$$

Where d_{50} is the sediment bed median particle diameter, s is the specific density of the sediment, g is the acceleration of gravity, and v is the kinematic viscosity of water. The Shields parameter for initiation of movement is used to calculate wave and current related critical shear stresses and can be estimated from grain size:

$$\theta_{cr} = b\,D_*^c \tag{2}$$

where b and c are coefficients based on the value of D_* such that the value of the Shields parameter approximate the well-known Shields curve (van Rijn 1993). The dimensionless bed shear stress parameter for bed-load transport T, and T_a at height a above the bottom (a is the height of the bed load layer) are estimated respectively by:

$$T = \frac{(\alpha_{cw}\,\mu_c\,\tau_{b,c} + \mu_w\,\tau_{b,w}) - \tau_{b,cr}}{\tau_{b,cr}} \tag{3}$$

$$T_a = \frac{(\alpha_{cw}\,\mu_c\,\tau_{b,c} + \mu_{w,a}\,\tau_{b,w}) - \tau_{b,cr}}{\tau_{b,cr}} \tag{4}$$

where α_{cw} is the wave-current interaction coefficient which is a function of bed roughness, wave boundary layer thickness, and water depth; μ_c is the current efficiency factor, which is a function of bed roughness and grain-size distribution; μ_w and $\mu_{w,a}$ are the wave efficiency factors at the bed

and at height a above the bed, respectively; μ_w and $\mu_{w,a}$ are a function of the grain-size distribution, bed roughness and wave conditions. The methods for estimating the four parameters are complex and the user is referred to van Rijn (1993) for additional details. In addition, $\tau_{b,c}$ is the current related bed shear stress; $\tau_{b,w}$ is the wave related bed shear stress; and $\tau_{b,cr}$ is the bed critical shear stress for the initiation of sediment resuspension. These shear stresses are calculated in the code and are based on currents, wave conditions, and friction factors. Other parameters calculated in the code include: backward and forward orbital velocities, active and boundary layer thickness, friction factors, and sediment mixing coefficients. Again, the user is referred to van Rijn (1989a,b; 1993) for details on their derivation.

Sediment Fluxes. The described parameters are then used to estimate time-varying bed load and time-averaged suspended load fluxes. These fluxes are then input to the LTFATE model to move sediment from cell to cell. The time-varying bed-load transport rate ($m^3/m/s$) is estimated as (van Rijn 1993):

$$\vec{q}_b(t) = 0.25\gamma\, \rho_s\, d_{50}\, D_*^{-0.3} \left[\frac{\vec{\tau}'_{b,cw}(t)}{\rho}\right]^{0.5} \left[\frac{\vec{\tau}'_{b,cw}(t) - \tau_{b,cr}}{\tau_{b,cr}}\right]^{1.5} \tag{5}$$

where $\gamma = 1 - (H_s/h)^{0.5}$, h is the water depth (m), H_s is the significant wave height (m), ρ is water density, ρ_s is the sediment density, $\tau_{b,cr}$ is the critical bed-shear stress according to Shields (N/m^2), and $\tau'_{b,cw}$ is the grain-related instantaneous (time-varying) bed shear stress due to currents and waves (N/m^2). In addition, $\vec{\tau}'_{b,cw}$ is related to both $\tau_{b,c}$ and $\tau_{b,w}$, but is not the sum of the two shear stresses. Summing wave and current related shear stresses has been shown to underestimate total bottom shear stress (Grant and Madsen 1979). The method used by van Rijn accounts for current and wave processes interactions to create a higher shear stress than the two components separately. Time-averaged values of $q_b(t)$ are obtained by averaging over a wave period.

Once it has been determined that the bottom shear stress exceeds the critical values for suspension, then an equilibrium volumetric reference concentration at a reference height $z = a$ above the sediment bed is calculated as:

$$C_{a,eq} = 0.015\, \frac{d_{50}\, T^{1.5}}{a D_*^{0.3}} \tag{6}$$

In addition, the concentration profile in the water column is calculated by:

$$\frac{dc}{dz} = \frac{\left[1 - c(z)\right]^5 c(z)\, w_s}{\varepsilon_{s,cw}(z)\left\{1 + \left[c(z)/c_o\right]^{0.8} - 2\left[c(z)/c_o\right]^{0.4}\right\}} \tag{7}$$

where c is the volume concentration, c_o is the maximum volume concentration (= 0.65), w_s is the particle settling speed, and $\varepsilon_{c,sw}$ is the combined current/wave sediment mixing coefficient (van

Rijn 1993). $\varepsilon_{c,sw}$ is a complicated function of wave, current, water, and sediment conditions. The user is referred to van Rijn (1993) for further details. The concentration profile is critical in determining the amount of suspended material that settles in each time-step. Deposition is based on the near-bottom concentration profile, not the vertically averaged concentration. Settling speed, w_s (cm/s), is estimated as a function of particle size by (Cheng 1997):

$$w_s = \frac{\nu}{d_{50}} \left[\left(25 + 1.2\, D_*^2 \right)^{1/2} - 5 \right]^{1.5} \tag{8}$$

Bed load and suspended fluxes across cell boundaries are then calculated and concentration and sediment bed elevation change updated. Suspended load flux in the direction of flow is calculated by:

$$q_s = \rho_s \int_a^h \bar{u}\, c(z)\, dz \tag{9}$$

where $\bar{u}$ is the vertically averaged velocity determined in the hydrodynamic section of LTFATE. Suspended and bed-load fluxes are divided into x and y direction fluxes within LTFATE. After bed load and suspended fluxes across cell boundaries are calculated, concentration and sediment bed elevation change are updated. This provides a new value of C_a. The resuspension flux from the bed to the water column at the next time-step is calculated using (van Rijn 1993):

$$E_{na} = w_s (C_a - C_{a,eq}) \tag{10}$$

Where E_{na} is the net resuspension flux from the sediment bed and C_a is the suspended sediment concentration at $z = a$, calculated by the fluxes across the cell elements. If $C_a < C_{a,eq}$, additional sediment can be carried by flow, so that erosion occurs and $E_{na} > 0$. Conversely, if $C_a > C_{a,eq}$, the carrying capacity of the water column at a particular bed shear velocity has been exceeded, which means that $E_{na} < 0$ and deposition can occur, even though the critical bed shear velocity has been exceeded. When bed shear velocity is less than the critical value or $C_a > C_{a,eq}$, the resuspension rate is zero and noncohesive sediments in the water column can be deposited on the sediment bed. The deposition flux is calculated as C_a multiplied by w_s.

RESULTS OF LTFATE MODEL: A sample simulation was performed and results shown here to demonstrate the new LTFATE sand code. Cell size was set at 15.24 m (50 ft) for this simulation and the grid was comprised of 61x61 cells in the x and y directions. Water depth surrounding the mound was 15.24 m (50 ft). Storm wave and current conditions are shown in Figure 1. U velocity is in the x-direction. Because this was a storm simulation, it was considered "short term" and data were input to the model through a "storm.dat" file. The user is referred to Scheffner et al. (1995) for formatting of this input file. A profile of the mound cross section in the x-direction before and after the storm event is shown in Figure 2. The combination of large waves and high current in the negative x-direction during this storm resulted in migration of the mound in the negative x-direction. In addition, mound peaks near the leading edge were reduced in height.